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# Studies on Semiconductor Structures, Laser-induced Oxidation and Orientationally-Disordered Crystals

R. Merlin  
January 16, 1989

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## FINAL REPORT

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### A. Quasiperiodic (Fibonacci) GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As Heterostructures

It has long been recognized that quasiperiodic (incommensurate) superlattices could offer interesting possibilities for experimental studies of novel physical phenomena. The major problem in fabricating such structures has been the fact that simple incommensurate modulations require increasingly larger layer thicknesses to approach the irrational limit. We have demonstrated that layer deposition in sequences generated by special production rules provide a solution to this problem. Superlattices grown according to these sequences show a degree of quasiperiodicity that is determined not by the width of the layers (which is arbitrary), but by the thickness of the samples. Our experimental and theoretical studies have concentrated on superlattices grown according to the Fibonacci sequence, i.e., Fibonacci Superlattices. We have elucidated their structural properties (showing self-similar behavior) and found an unexpected robustness of the quasiperiodic ordering respect to growth-parameter fluctuations which is still poorly understood. We have also demonstrated a link between (non-resonant) Raman scattering by acoustic phonons and x-ray scattering, and obtained resonant data revealing the expected hierarchy of gaps in the phonon spectrum. Using a tight-binding approach, we have investigated impurity states in Fibonacci lattices in an effort to introduce a concept analogous to the effective-mass of periodic systems. We find that the "mass" shows quasiperiodic behavior in a scale that is much larger than that of the lattice and which depends on the size of the impurity. Heavier carriers are associated with larger impurity sizes.

### B. Shallow Impurities in Quantum-Well Structures

Shallow impurities in semiconductor quantum-well structures form quasi-two-dimensional hydrogenic systems whose parameters can be both easily varied and controlled with great accuracy. The features of interest for these systems include (i) confinement-induced splittings and shifts of impurity levels and (ii) broadening of impurity-related features originated in the dependence of the spectrum on the position of the impurity in a well. As a continuation of our early Raman work on Si-donors in GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As quantum-wells, we have

pursued an investigation of the spectrum of Be-acceptors. Both center- and edge-doped samples were investigated. The data show energy shifts and clearly resolved splittings of the ground state  $1S_{3/2}[\Gamma_8]$  and the excited state  $2S_{3/2}[\Gamma_8]$  due to quantum confinement. The results allow a precise determination of transition energies that can be compared with theoretical predictions. The spectra also reveal some unexpected features: coupling of resonant impurity states to optical phonons and intensity transfer of acceptor transitions as a function of temperature. An identification of these effects is under current investigation.

### C. Magnetic-Field-Enhanced Raman Scattering by Optical Phonons in Semiconductor Superlattices

We have discovered a dramatic (orders of magnitude) enhancement of the scattering by interface and confined phonons in quantum-well structures in the presence of magnetic fields normal to the layers. Interface Raman scattering is, in general, defect-induced. Our work has established that defects are also responsible for the enhancement of both interface and confined modes. In a related investigation, we have found that strong photoexcitation leads to quenching of the interface-phonon features. Comparisons with calculations of spectral lineshapes indicate that the dominant form of electron-phonon coupling is the Fröhlich interaction. The nature of the defect (or defects) that can be turned on by magnetic fields and turned off by photoexcitation remains unsettled. Possible candidates are interface-roughness and ionized impurities. Experiments are being pursued to explore these alternatives.

### D. Subband-Landau-Level Coupling in Tilted Magnetic Fields

In quasi-two-dimensional electron systems, magnetic fields at angles  $\theta \neq 0$  with respect to the superlattice axis lead to mixing between the in-plane cyclotron motion and the subbands. Perturbation theory predicts a positive diamagnetic shift for the subbands and subband-Landau level anti-crossing with a minimum splitting  $\propto \theta$ . These results are only valid when  $\theta \ll 1$  and when the cyclotron energy is small compared to intersubband separations. These conditions are not always met in experiments: large angles or fields are often required to bring particular levels close together. To approach these situations, we have studied in detail the properties of parabolic wells in the presence of tilted fields. This

problem can be solved analytically and its solution reveals features which are not apparent in results based on perturbation theory. In particular, we find that a gap always exists in the spectrum of coupled excitations and that the diamagnetic shifts can be of either sign. We have also shown that the effect of tilted fields in square wells is well described by expressions valid for the parabolic case in situations where the coupling to higher subbands can be neglected. We have studied the coupled (electron) intersubband-cyclotron modes in  $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$  quantum-wells using Raman scattering. The cyclotron mode is nominally Raman forbidden, but it becomes allowed through the coupling to intersubband excitations. Thus, tilted fields allow a determination of the effective-mass using our technique. The results of our experiments confirm the theoretical model and reveal the expected non-parabolic behavior of the effective-mass.

## Publications

Funding Document DAAG29-85-K-0175

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### A. Journals

1. "Quasiperiodic GaAs-AlAs Heterostructures", R. Merlin , K. Bajema, R. Clarke, F.-Y. Juang and P.K. Bhattacharya, Phys. Rev. Lett. **55**, 1768 (1985).
2. "Evidence of a High-Temperature Dipole-Glass Phase in  $K_2CrO_4$ ", S. Russell and R. Merlin , Phys. Rev. **B33**, 1871 (1986).
3. "Raman Spectra of Shallow Acceptors in Quantum-Well Structures", D. Gammon , R. Merlin , W.T. Masselink and H. Morkoc, Phys. Rev. **B33**, 2919 (1986).
4. "Inelastic Light Scattering by Electronic Excitations in Semiconductor Heterostructures", (invited contribution), G. Abstreiter, R. Merlin , and A. Pinczuk, IEEE J. Quantum Electron. **QE-22**, 1771 (1986).
5. "Synchrotron X-Ray Study of a Fibonacci Superlattice", J. Todd, R. Merlin , R. Clarke, K.M. Mohanty and J.D. Axe, Phys. Rev. Lett. **57**, 1157 (1986).
6. "Magnetic-Field-Enhanced Raman Scattering by Confined and Interface Phonons in Semiconductors Superlattices", D. Gammon , R. Merlin and H. Morkoc, Phys. Rev. **B35**, 2552 (1987).
7. "Raman Scattering by Acoustic Phonons in Fibonacci GaAs-AlAs Superlattices", K. Bajema and R. Merlin , Phys. Rev. **B36**, 4555 (1987).
8. "Subband-Landau-Level Coupling in Tilted Magnetic Fields: Exact Results for Parabolic Wells", R. Merlin , Solid State Comm. **64**, 99 (1987).
9. "Structural and Electronic Properties of Non-Periodic Superlattices", (invited contribution), R. Merlin , IEEE J. Quantum Electron. **24**, 1791 (1988).
10. "Suppression of Raman Scattering by Interface Phonons in Quantum Wells under Strong Photoexcitation", G. Ambrazevicius, M. Cardona, R. Merlin and K. Ploog, Solid State Comm. **65**, 1035 (1988).

11. "Raman Studies of Fibonacci, Thue-Morse and Random Superlattices". (invited contribution), R. Merlin , to be published in *Light Scattering in Solids V*, Topics in Applied Physics Vol. 66 (Springer, Berlin, 1989).

#### B. Conference Proceedings

1. "Fibonacci GaAs-AlAs Superlattices", presented at the Second International Conference on Phonon Physics, Budapest, 1985. R. Merlin , K. Bajema, R. Clarke, F.-Y. Juang and P.K. Bhattacharya, in *Phonon Physics*, ed. by J. Kollar and N. Kroo, N. Menyhard and T. Siklos (World Scientific, Singapore, 1985), p. 541.
2. "Artificially Structured Incommensurate Materials", presented at the NATO Advanced Research Workshop on Incommensurate Materials, Boulder, 1986 (invited contribution), R. Clarke and R. Merlin , in *Incommensurate Crystals, Liquid Crystals and Quasicrystals*, ed. by J. Scott and N.A. Clark (Plenum Press, New York, 1987), p. 359.
3. "Quasiperiodic Semiconductor Superlattices", presented at the 18th International Conference on the physics of Semiconductors, Stockholm, 1986, R. Merlin , K. Bajema, R. Clarke and J. Todd, in *18th International Conference on the Physics of Semiconductors*, ed. by O. Engstrom (World Scientific, Singapore, 1987), p. 675.
4. "Acceptor Raman Scattering in GaAs-(Al, Ga)As Quantum-Well Structures", presented at the Fourth International Conference on Molecular Beam Epitaxy, York, 1986. D. Gammon , R. Merlin , H. Huang, and H. Morkoc, *J. Crystal Growth* **81**, 149 (1987).
5. "Growth and Properties of Quasiperiodic Structures", presented at the Fourth International Conference on Molecular Beam Epitaxy, York, 1986. R. Clarke, J. Todd, R. Merlin , K. Bajema, P.K. Bhattacharya and F.-Y. Juang, *J. Crystal Growth* **81**, 116 (1987).
6. "Raman Scattering by Acoustic Phonons and Structural Properties of Fibonacci, Thue-Morse and Random Superlattices", presented at the Third International Conference on Modulated Semiconductor Structures, Montpellier, 1987, R. Merlin , K. Bajema, J. Nagle and K. Ploog, *J. Phys.* **48**, C-5 503 (1987).

7. "Observation of Coupled Quasi-Two-Dimensional Electronic Excitations in Tilted Magnetic Fields", presented at the 7th International Conference on Electronic Properties of Two-Dimensional Systems, Santa Fe, 1987. R. Borroff , R. Merlin , R.L. Greene and J. Comas, Surf. Sci. **196**, 626 (1988).
8. "Enhanced and Quenched Raman Scattering by Interface Phonons in Semiconductor Superlattices: What are the Defects?", presented at the Third International Conference on Superlattices, Microstructures and Microdevices, Chicago, 1987. D. Gammon, L. Shi , R. Merlin , G. Ambrazevicius, K. Ploog and H. Morkoc, Superlattices and Microstructures **4**, 405 (1988).

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